Design of Modularized Polymer Fluid Control Device System and Research on Polymer Flow Parameters

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Abstract: This study designs a modular polymer fluid control device, which realizes the flexible regulation of different injection parameters (aperture, position, temperature) and basin structure (single cavity/double cavity splicing) through the standardized cubic cavity structure and replaceable injection module. Combined with the numerical simulation method of Computational Fluid Dynamics (CFD), the flow behavior of polyurethane fluids under different conditions is systematically investigated, and the quantitative relationship of parameters-flow-performance is established, which provides the theoretical basis and technical support for the optimization of the polymer processing process. The study not only helps to deeply understand the rheological characteristics of polymer fluid, but also provides guidance for complex mold design, intelligent process control, etc., and promotes polymer material processing technology to develop in the direction of high efficiency and precision. This research idea not only ensures the experimental feasibility, but also obtains conclusions of general significance, which sets the foundation for the flow analysis of more complex structures.

Keywords:Polymer Fluid; Control Device System; Polymer Flow Parameters; Flow Analysis

1. Introduction

In the field of precision molding such as microfluidic device fabrication , the cubic cavity structure is typical representative. The study of the flow characteristics of polymer fluids in the simplified model can provide an important reference for the selection of injection molding process parameters for complex microstructures. Especially in biomedical device manufacturing, the flow homogeneity and filling integrity of the melt are directly related to the functional realization of the device, and the experimental data and simulation results of this study can provide technical support for the molding quality control of such precision devices[1-2]. From the perspective of material processing, this study is also of guiding significance for the preparation of functional composites. In the processing of filled polymer composites, the melt flow state will significantly affect the distribution and orientation of functional fillers. By studying the flow characteristics under different injection conditions, scholars can better control the distribution state of the fillers and thus optimize the performance of the materials[3-5], which is of practical application value for the development of composite products with specific functional requirements.

Polymers have a wide range of applications in numerous fields[6-10], Polyurethane materials also exhibit good energy absorption properties[11-12], Polymers, also known as high-molecular polymers, are macromolecular materials composed of a large number of repetitive structural units connected by covalent bonds, including plastics, rubber, fibers, coatings, etc., which are widely used in industrial production and daily life. Polymer fluids have unique rheological properties, which are mainly manifested in non-Newtonian fluid behavior[13], including shear thinning (or shear thickening), viscoelasticity, normal stress effect, etc[14]. These properties make polymer fluids prone to instability in the flow process, such as extrusion swelling, melt rupture, wall slip, etc., which seriously affects processing accuracy and product quality.

Polyurethane (PU) is a kind of block copolymer formed by the polymerization of polyols and isocyanates. Its molecular chain contains flexible soft segments (such as polyether / polyester) and rigid hard segments (such as isocyanates)[15]. This unique microphase separation structure makes it have highly adjustable mechanical properties, excellent wear resistance, chemical resistance and diverse morphology[16]. By adjusting the ratio of raw materials or introducing functional components (such as nanofillers and bio-based monomers), the performance customization of polyurethane can be further realized to meet the needs of different application scenarios such as automotive parts, medical devices and flexible electronic devices.

Finite element simulation technology plays a key role in this study, which provides a new technical path for polymer fluid control research. Through the establishment of a multi-physical field coupling model, the interaction of the flow field, temperature field and stress field can be analyzed more comprehensively, and the flow characteristics of the polymer fluid in the control device can be understood in depth. This numerical simulation method can not only make up for the shortcomings of traditional experimental studies, but also provide a theoretical basis for the optimal design of the device. In this study, the simulation technique realizes the multi-scale analysis from microscopic to macroscopic, which helps to reveal the rheological mechanism of polymer fluid under controlled conditions and lays the foundation for the development of more efficient control strategies.

2. Structural Design ofthe Flow Control Device

The polymer fluid flow control device designed in this study is based on the basic research needs in the field of polymer material processing, and the multi-dimensional regulation of flow behavior is realized through a well-designed structural scheme. The design of the structure is based on the Solid Works 3D design software platform, and the polymer fluid flow control device is developed by parametric modeling method.

In the structural design stage, the powerful SolidWorks solid modeling and assembly functions were fully utilized to achieve the accurate design of the device components. The main body of the device adopts the standard cubic cavity structure of 300mm×300mm×300mm, which not only ensures enough observation space, but also avoids the waste of materials and inconvenience of experimental operation caused by too large size. In terms of function realization, the innovative design of the top replaceable injection cover can realize the switching of different injection apertures through simple module replacement. Nine injection holes are distributed axisymmetrically in the top cover, which can meet the different requirements for the injection position under different working conditions, and the holes that are not involved in the injection can be blocked with rubber plugs during the experiments. The device is equipped with rubber seals, which can be replaced according to the research needs of the module and can also meet the sealing requirements during the experimental process. It is especially worth mentioning that the device is equipped with three standard sizes of 10mm, 15mm and 20mm injection module, these precision machining of the module not only ensures the accuracy of the experimental data, but also visualize the flow characteristics of different pore sizes under the conditions of the changing law. Figure 1 and Figure 2 below are the schematic structure and explosion diagram of the polymer fluid control device designed in this study.At the level of research methodology, this study adopts a simulation-based approach, using a simplified model to systematically study the effect of injection conditions on the flow characteristics of the law.

In terms of extended functionality, the device adopts an innovative bolt-on detachable sidewall structure, so that when a multi-cavity flow experiment is required, as in Figures 3, multi-cavity splicing can be easily realized by simply removing the side panels. This design not only ensures the structural strength and sealing performance when the cavities are combined, but also realizes the rapid configuration of multi-cavity flow experiments. Through simple disassembly and reorganization, researchers can build a variety of cavity combinations in series and parallel, which provides a convenient way to study the flow behavior under complex flow conditions.

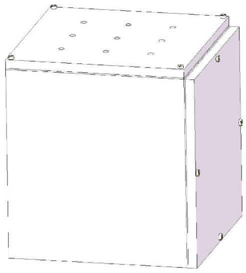


Figure 1. Polymer Fluid Control Device Structure Schematic Diagram

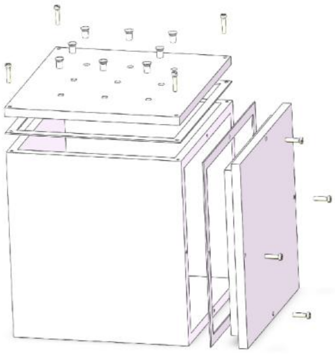


Figure 2. Exploded View of the Polymer Fluid Control Device

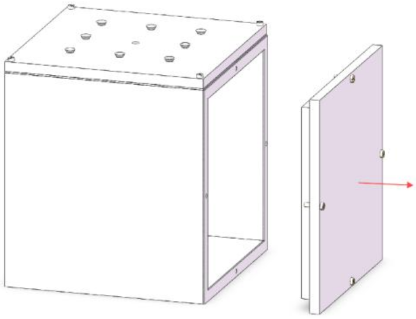


Figure3. Side Plate Disassembly

The design of this polymer fluid flow control device in the choice of materials for full consideration, with special attention to the visualization needs of the experimental process. The main structure of the device is made of acrylic (PMMA) sheet, a material that not only has excellent light transmission for direct observation of the flow process of polymer fluids, but also has good chemical stability and can withstand the corrosion of common polymer fluids. After testing, the acrylic material in the experimental temperature range showed good dimensional stability and chemical resistance, fully meet the requirements as a polymer fluid container.

In the specific structural design, I through SolidWorks software to optimize the thickness of the acrylic sheet design, to ensure that when subjected to experimental pressure can still maintain good transparency and structural strength. The key sealing parts of the device using rubber seals, not only to ensure the sealing performance, but also to avoid the problem of material corrosion. The easy processing characteristics of the acrylic material greatly reduces the manufacturing cost, so that the device can make multiple spare components to facilitate rapid switching between different experimental conditions. This material selection program to ensure experimental accuracy at the same time, greatly enhancing the practicality and economy of the device, especially suitable for teaching experiments and basic research.

In terms of synergistic research between experiment and simulation, all the key dimensional parameters of the device are carefully designed to maintain a high degree of correspondence with the finite element analysis model. This correspondence ensures that the experimental data can be directly used for the verification and correction of the simulation model, which greatly improves the research efficiency. All contact surfaces of the device adopt precision machining process, which effectively reduces the interference of boundary effects on the flow behavior and provides a guarantee for obtaining accurate experimental data.

The design of the device fully embodies the concept of "simple and practical, clear function", and under the premise of guaranteeing the basic research function, it realizes the coverage of various experimental scenarios through the ingenious modular design. From the perspective of basic research, the device can provide reliable experimental data for the study of polymer rheology; from the perspective of engineering application, its research results can directly guide the optimization and improvement of the production process. It is especially worth pointing out that the standardized and modular design of the device not only reduces the manufacturing cost, but also greatly improves the ease of use and maintainability of the device. Through the systematic study of the flow behavior under different injection parameters, the device will provide important technical support for the in-depth understanding of the polymer flow mechanism, optimize the processing parameters, and build a bridge between basic research and engineering applications in the field of polymer materials processing.

3.Analysis of Polymer Flow Theory

Finite element simulation, as an important means to study the behavior of polymer fluid flow, is implemented in this study using ANSYS Fluent, a professional computational fluid dynamics (CFD) software. Computational fluid dynamics is a technique for solving the equations of motion and control of fluids by numerical methods, which can predict the flow characteristics of fluids, heat and mass transfer processes, and other complex physical phenomena without actual physical experiments.ANSYS Fluent, as one of the most dominant CFD simulation tools at present, has a powerful solving capability and a rich variety of physical models, which is particularly suitable for dealing with non-Newtonian fluids, multi-phase flow and other complex flow problems. The software uses the finite volume method to discretely solve the Navier-Stokes equations, and can accurately simulate the flow process of polymer fluid in the control device through reasonable mesh delineation and boundary condition settings.

In this study, the VOF (Volume of Fluid) multiphase flow model is used to accurately simulate the dynamic behavior of the interface between the two phases of polyurethane (PU) melt and air.The VOF model constructs and traces the free surface according to the volume function of the fluid in the grid cell at each moment, F. If F is in the grid cell at a certain moment, the free surface can be traced. If F=1 in a grid cell at a certain moment, it means that the cell is occupied by the specified phase fluid, and it is a fluid cell; if F=0, the cell is occupied by the other phase fluid, and it is called an empty cell with respect to the former phase fluid; when 0<F<1, the cell is an interfacial cell which contains two-phase substances. The continuity equation, volume fraction continuity equation and momentum equation are:

$$\frac{\partial^{o}}{\partial_t}-\nabla\cdot\ (\rho_v)=0 \quad (1)$$

$$\frac{\partial\alpha_{\mathrm{i}}}{\partial_{\mathrm{t}}}+v\cdot\nabla(\alpha_{\mathrm{i}})=0 \quad (2)$$

$$\&\frac{\partial(\rho_{\mathrm{v}})}{\partial_{\mathrm{t}}}-\nabla\cdot(\rho_{\mathrm{vv}})=-\nabla\mathrm{p}^{-}\nabla\cdot[\mu_{\nabla}\mathrm{v}^{+}\nabla\mathrm{v}^{\mathrm{T}})]+\rho_{\mathrm{g}}+\mathrm{F} \quad (3)$$

$$\alpha_1+\alpha_2=1 \quad (4)$$

$$\rho=\alpha_2\rho_2+(1-\alpha_2)\rho_1 \quad (5)$$

$$\mu=\alpha_2\mu_2+(1-\alpha_2)\mu_1 \quad (6)$$

The source term of the momentum equation due to surface tension and wall adhesion is.

$$\mathrm{F}=2\sigma_{\mathrm{ij}}\rho ki\nabla\alpha_{\mathrm{i}}/(\rho_{\mathrm{i}}+\rho_{\mathrm{j}}) \quad (7)$$

In the above equations,ρ is the density;v is the velocity vector; μ is the hydrodynamic viscosity;α_{i} is the volume fraction of phase i;k is the surface curvature; and the subscripts 1 and 2 stand for air and liquid, respectively.

For the turbulent state of polymer fluid that may occur during the high-speed injection process, the standard k-ε two-phase dual-equation turbulence model is used in this study to characterize the turbulence of the flow. k-ε turbulence model was proposed by Launder and Spalding[20] . The standard k-ε model ignores the viscosity between molecules and considers the ideal case where the flow field is in a fully turbulent state and is suitable for dealing with fully developed turbulence. The transport equation for the turbulent kinetic energy and the transport equation for the turbulent dissipation rate are as follows[21] :

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial\left(\rho k u_j\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \quad (8)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial\left(\rho\varepsilon u_j\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\frac{\varepsilon}{k}C_{\varepsilon1}(G_k+C_{\varepsilon3}G_b)-\frac{\rho C_{\varepsilon2}\varepsilon^2}{k}+S_\varepsilon \quad (9)$$

The expression for turbulent viscosity is given by:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \quad (10)$$

where the empirical constants C_μ =0.09, $C_{\varepsilon1}$ =1.44,$C_{\varepsilon2}$ =1.92,σ_k =1.3,σ_ε =1.0; ,G_kG_b are turbulent kinetic energy generating terms, Y_M is the effect of compressibility of the fluid,S_k ,S_ε are user-defined source terms.

In the numerical simulation of this study, a 3D geometrical model identical to the experimental setup is firstly required, which is usually accomplished by CAD software and imported into Fluent.Subsequently, mesh delineation is carried out, and considering the viscous nature of the polymer fluid, mesh encryption is required in the near-wall region to capture the boundary layer effects. The choice of physical model is particularly critical.

For the non-Newtonian characteristics of polymer fluids, appropriate constitutive equations such as the power law model or the Carreau model are used to describe the viscosity change. The boundary conditions are set with strict reference to the experimental conditions, including the injection speed, pressure outlet and other parameters. The choice of solver and parameter settings also need to be optimized according to the specific problem, and a pressure-based solver with appropriate discrete format is usually used.

In this study, the numerical simulation of polymer fluids carried out by ANSYS Fluent, a CFD platform, not only predicts the flow pattern, pressure distribution and other key parameters, but also verifies with the experimental results to form a complete research closed loop. This "experiment-simulation" combined research method not only overcomes the high cost of pure experimental research, the shortcomings of the difficult parameter control, but also avoids the pure numerical simulation of the model distortion problems that may exist for a deeper understanding of the behavior of polymer fluid flow provides a reliable means of research.

After generating the body mesh, switch Fluent to the solution mode and start to set the environment conditions for simulation. First of all, in the general settings, select the "pressure-based-absolute-steady-state" solver, because the research process will be the influence of gravity on the polymer fluid into the scope of the study, so in the y-direction of the acceleration of gravity "-9.8m/s²". Then, before setting up the computational model, a new fluid parameter is created, which is polyurethane (PU), the polymer fluid material used in this study. In this numerical simulation, the relevant material parameters of polyurethane fluid refer to the PU material parameters used by Prof. Li Xiaolong et al. in the study of the effect of temperature on the diffusion characteristics of the polymer slurry in the fracture, as follows in Table 1.

Table 1. Parameters of Polyurethane Fluid Materials Used in This Project

Density /(kg-m^{-3})	Specific heat /(J·kg^{-1}·K^{-1})	Thermal conductivity /(W·m^{-1}·K^{-1})	Viscosity /(kg·m^{-1}·s^{-1})
1100	1800	0.2	1

4. Setting Solution

4.1 Selection of Solution Mode

Solver settings. In Fluent, the configuration of the solver is the key to successful simulation. The type of solver used in this simulation is "pressure based", which is suitable for dealing with high viscosity fluid flow problems such as polymer slurries. The speed format is set to "absolute speed" to ensure an accurate reflection of the true motion state of the fluid during the calculation process. Due to the fact that the flow process of polymer slurries often involves time-dependent transient phenomena, the time is set as "transient" to capture the dynamic changes during the flow process. In addition, considering gravity's influence on flow, gravity's magnitude is set to 9.81 m/s ² and the direction is in the negative y-axis direction to simulate the natural flow behavior of fluids in a gravity field.

Model selection. In order to accurately simulate the interaction between polymer slurry and air, the "VOF" (Volume of Fluid) analysis method in multiphase flow models was selected. This method simulates the interface of multiphase flow by tracking the volume fractions of different phases, which can effectively capture the dynamic changes of fluid interfaces. In the model settings, check the "Implicit Volume Force" option to ensure that the influence of volume force can be accurately considered during the calculation process, thereby improving the stability and accuracy of the simulation.

Choose accordingly. In the phase setting, two phases are defined: air phase and high polymer fluid phase. The air phase represents the gas environment inside the mold, while the polymer fluid phase is the main object of this study. By clearly distinguishing between these two phases, it is possible to more accurately simulate the flow behavior of polymer slurries in air, as well as the interactions between the two.

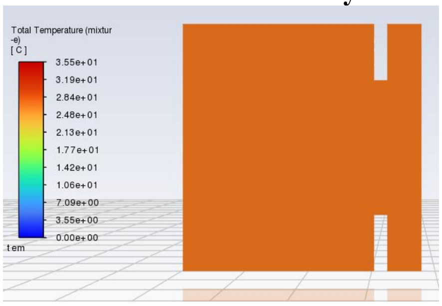
Interphase interaction. In the setting of interphase interactions, surface tension is a key parameter. In this simulation, the surface tension was set to 0.038 N/m, which reflects the interfacial tension characteristics between the polymer slurry and air. Select the "Continuous Surface Tension" option in the "Surface Tension Model" and further check the "Wall Adhesion" function to simulate the adhesion behavior of polymer slurry on the mold wall. These settings help to more accurately reflect the physical phenomena during the flow process, especially the behavior near the interface.

Boundary condition setting. In the boundary condition setting, the entrance velocity is set to a constant with a velocity value of 1 m/s. This setting ensures that the fluid enters the mold at a constant velocity, providing a stable initial condition for flow analysis. In terms of solving time settings, different pressure velocity coupling schemes are adopted based on the simulated transient or steady-state characteristics. When the solution time is set to transient, the Simple scheme is adopted, combined with standard initialization methods to ensure the stability and convergence of the simulation; When the solution time is set to steady state, the Coupled scheme is used, combined with a hybrid initialization method, to improve computational efficiency and ensure the accuracy of the results.

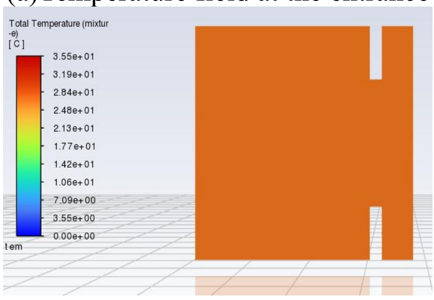
Time step and time step number settings. In Fluent, "Time Step Size" and "Number of Time Steps" are two key parameters in transient simulation, which together control the time progression process of the simulation. The time step represents the interval between each time advancement, and its size has a significant impact on the accuracy and computational stability of the simulation. A smaller time step can capture the details of transient flow more accurately, but it will significantly increase computation time and resource consumption; Although a larger time step can accelerate the calculation speed, it may lead to inaccurate simulation results and even computational divergence in areas with severe flow changes. Therefore, the setting of the time step needs to be balanced based on the specific characteristics of the problem. For example, in the process of filling molds with high polymer slurry, if the flow changes slowly, the time step can be set to 0.1 seconds to 1 second; For situations involving rapid reactions or drastic flow changes, such as the rapid solidification reaction of polymer slurries, the time step may need to be set to 0.01 seconds or even smaller. The number of time steps determines the total time range of the simulation, that is, the number of time steps from the initial time until the calculation stops. By setting a reasonable number of time steps, it can be ensured that the simulation can cover key events and changes throughout the entire flow process. If the number of time steps is too small, it may not be possible to fully capture the flow process, such as stopping the calculation before the high polymer slurry is fully filled or solidified in the mold; However, having too many time steps can lead to unnecessary waste of computing resources. Therefore, when setting the number of time steps, it is necessary to consider the actual flow process and research objectives comprehensively..

Selection of viscosity model. In the selection of the viscous model, the laminar model was chosen instead of the turbulent model for this simulation. This choice is based on the consideration of the rheological properties and flow state of the polymer slurry. Polymer slurries typically have high viscosity, and their flow process often exhibits laminar flow. In laminar flow, the motion trajectory of the fluid is an orderly parallel line, with layered flow and no obvious lateral mixing between the layers. This flow state usually occurs at low Reynolds numbers, and is generally considered laminar when the Reynolds number is less than 2000. In laminar flow, the viscosity of the fluid plays a dominant role, and momentum transfer is mainly achieved through molecular motion. The flow is relatively smooth and is less prone to the vortices and mixing phenomena commonly seen in turbulence. In contrast, turbulence is a more complex flow state characterized by the chaotic motion trajectories of fluid particles. In addition to moving along the mainstream direction, pulsations are also perpendicular to the mainstream direction. Turbulence usually occurs at high Reynolds numbers, and generally can be considered turbulence when the Reynolds number is greater than 4000. In turbulence, inertial forces play a dominant role, and momentum transfer is achieved not only through molecular motion, but also through the motion of turbulent eddies. Mixing and diffusion in turbulence are much stronger than in laminar flow. However, the high viscosity characteristics of polymer slurries make them more inclined to maintain laminar flow during the flow process, and even at higher flow rates, it is difficult to achieve turbulent Reynolds number conditions. Therefore, choosing a laminar flow model can more accurately reflect the flow characteristics of polymer slurries and avoid the complex calculations and potential instability caused by turbulent models.

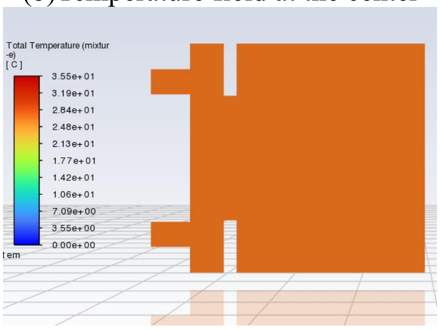
4.2 Simulation Results and Analysis



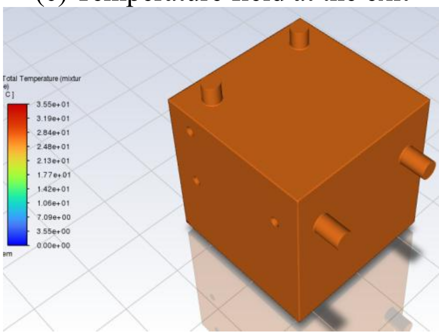
(a)Temperature field at the entrance



(b)Temperature field at the center



(c) Temperature field at the exit



(d) Isometric view of temperature field

Figure 4. Temperature Field Inside the Mold with a Viscosity of 300 Pas

From Figure 4(a)、(b)、(c)、(d), it can be seen that under the condition of viscosity of 300 Pa·s, the grouting speed is 1m/s, and the simulation of phase selection is air phase and high polymer fluid phase. As shown in the figure, the temperature field cloud maps at the entrance, central position, and exit are all within the range of around 28.4 ℃. From the isometric view, it can be seen that the temperature of polyurethane will only fluctuate within a minimal range during flow and will not undergo significant changes. According to the description of the flow and diffusion of polymer materials in the previous text, an elliptical diffusion pattern is observed in the injection mold fixture after the reaction. In the inlet area, the temperature remained stable at 28.4 ± 0.2 ℃, indicating that the polymer fluid did not experience significant temperature rise due to shear heating or friction effects during high-speed injection; In the central diffusion region, the temperature distribution is uniform with a range not exceeding 0.3 ℃, verifying the buffering effect of polyurethane's low thermal conductivity (0.2 W/(m·K)) on the temperature field; In the export area, the temperature remains consistent with the inlet (28.4 ℃), indicating that the fluid did not undergo significant heat exchange with the outside during the entire process of flowing.

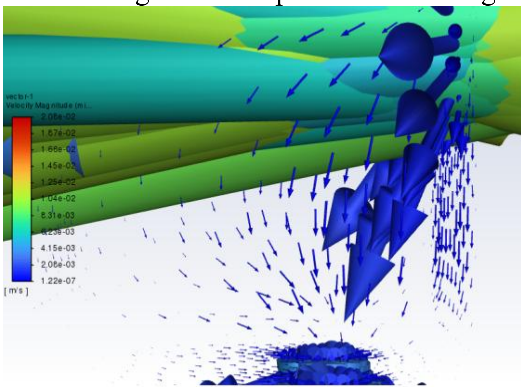


Figure 5. Temperature Field Vector Diagram

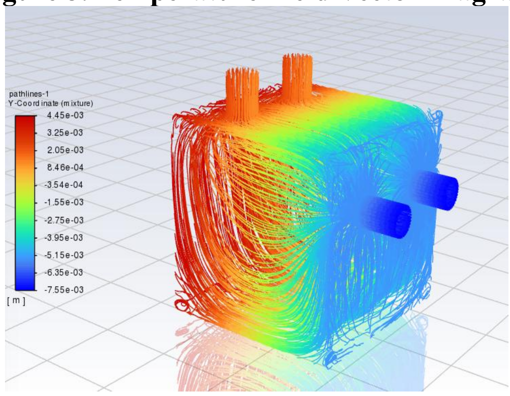


Figure 6. Temperature Field Trace Diagram

According to the temperature field vector diagram in Figure 5, the blue arrows indicate the direction of fluid flow, and the arrows' density and length reflect the flow velocity's magnitude. It can be seen that the fluid flow velocity is faster in the inlet and outlet areas, while the velocity is slower in the cavity area inside the mold, which may be related to the complexity of the geometric structure, such as narrow channels or obstacle positions. The temperature of fluids varies in different regions, which may be due to heat exchange between the fluid and the surrounding environment or solid walls in different temperature regions during the flow process. The temperature in the inlet and outlet areas is relatively high and may be close to the heat source or heat input point, while the temperature in other areas is lower.

Figure 6 shows the trajectory of the temperature field inside the mold, with color bars indicating the range of temperature changes, from blue (lower temperature) to red (higher temperature). The fluid has a higher temperature at the inlet, and as it flows inside the mold, the temperature gradually decreases. In the front and upper lower boundary areas of the mold, the temperature change of the fluid is more obvious, which may be due to slow flow velocity or local heat dissipation in these areas.

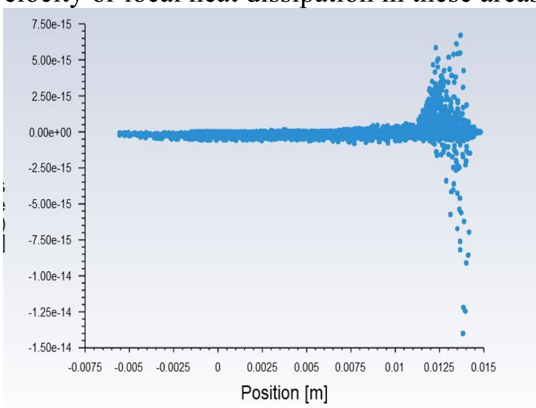
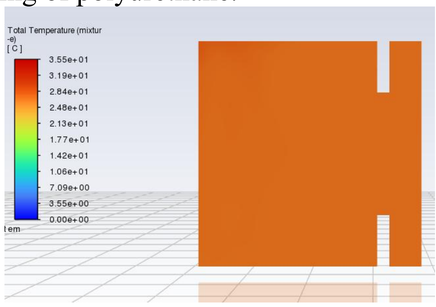
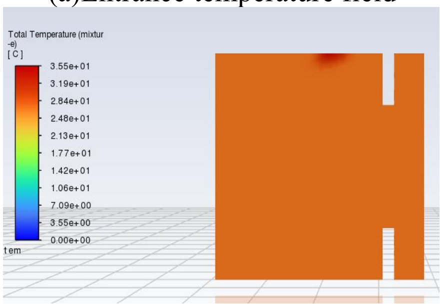


Figure 7. Temperature Field Scatter Diagram

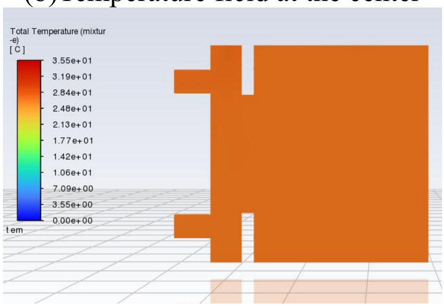
Figure 7 shows the temperature field scatter plot, from which it can be seen that the temperature values of most data points are concentrated around 12.6℃, indicating a relatively uniform temperature distribution inside the mold. This indicates that during the simulation process, the temperature change of the polyurethane fluid is relatively small, and the thermal environment inside the mold is relatively stable. The uniformity of this temperature helps to ensure the stable flow and curing of polyurethane in the mold, reducing uneven flow and internal stress caused by temperature differences. The temperature values of a small number of data points in the figure deviate far from 12.6 ℃, which may correspond to certain special areas in the mold, such as near the inlet or outlet, where there may be local temperature fluctuations or measurement errors. overall, the temperature field inside the mold is relatively stable, providing favorable thermal conditions for the molding of polyurethane.



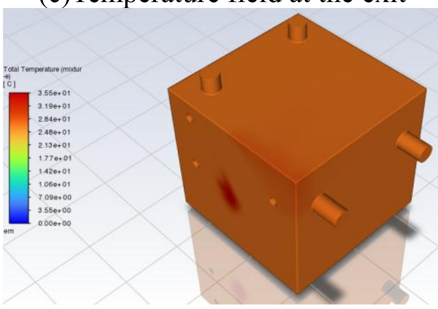
(a)Entrance temperature field



(b)Temperature field at the center



(c)Temperature field at the exit



(d)Isometric view of temperature field

Figure 8.Temperature Field Inside the Mold with a Viscosity of 400 Pa·s

From Figure 8(a)、(b)、(c)、(d), it can be seen that under the condition of viscosity of 400 Pa · s, the grouting speed is maintained at 1m/s, and the fluid phase is still selected as air phase and high polymer fluid phase for simulation. The temperature field at the inlet and outlet remains within the range of around 28.4 ℃, indicating that even with an increase in viscosity, the temperature changes of the polyurethane fluid during the flow process in these areas are still not significant. Although the temperature field in the central position is slightly higher in the upper area, reaching around 35.5 ℃, the overall temperature field remains constant. This temperature distribution indicates that although changes in viscosity may have certain effects on fluid flow, such as increased flow resistance, their impact on the temperature field is relatively limited. From the isometric view, it can be observed that the temperature fluctuation range of polyurethane during the flow process is extremely small, which further confirms that even if the fluid viscosity changes, it will not cause significant changes in the temperature field. This phenomenon can be attributed to the low thermal conductivity of polyurethane materials (0.2 W/(m · K)), which can effectively buffer temperature changes during the flow process and maintain the stability of the temperature field. In addition, this temperature stability also indicates that the fluid flow in the mold has not undergone significant heat exchange with the external environment, maintaining good thermal insulation.

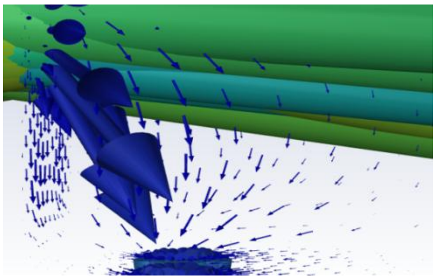


Figure 9. Temperature Field Vector Diagram

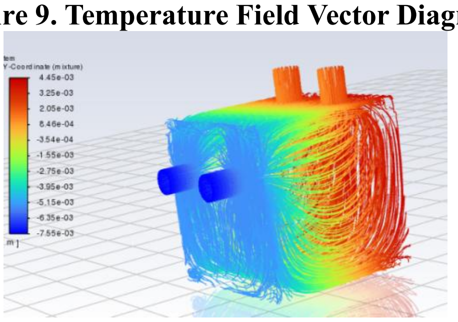


Figure 10. Temperature Field Trace Diagram

From Figure 9, it can be observed that the fluid flow rate is faster at the inlet and outlet of the mold, while the flow rate is slower in the cavity area inside the mold. This is likely due to the complexity of the internal structure of the mold, such as the presence of narrow channels or obstacles. The temperature of fluids varies in different regions, which may be due to heat exchange between the fluid and the surrounding environment or solid walls at different temperatures during the flow process. The temperature in the inlet and outlet areas is higher, possibly because these areas are closer to the heat source or heat input point, while the temperature in other areas is relatively lower.

Figure 10 shows the temperature field trace inside the mold, with color bars indicating the range of temperature changes, from blue (lower temperature) to red (higher temperature). The temperature of the fluid at the inlet is relatively high, and as it flows inside the mold, the temperature gradually decreases. At the junction of the front and bottom of the mold, the temperature change of the fluid is more obvious, which may be due to slow flow velocity or local heat dissipation in these areas.

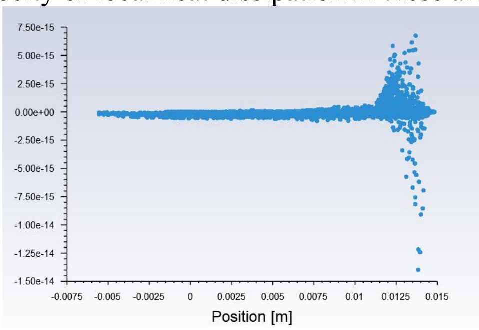
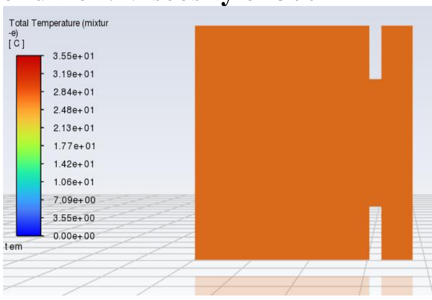


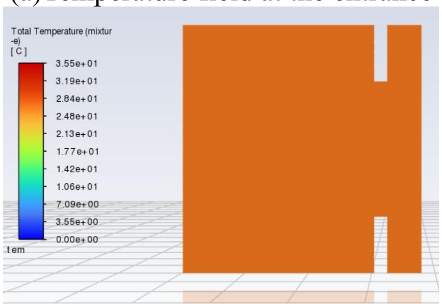
Figure 11.Temperature Field Scatter Diagram

Figure 11 is a temperature field scatter plot, from which it can be seen that the temperature values of most data points are concentrated around 12.6 ℃, indicating a relatively uniform temperature distribution inside the mold. This indicates that during the simulation process, the temperature change of the polyurethane fluid is not significant, and the thermal environment inside the mold is relatively stable. The uniformity of this temperature helps ensure stable flow and curing of polyurethane in the mold, reducing uneven flow and internal stress caused by temperature differences. The temperature values of a few data points in the figure differ significantly from 12.6 ℃, which may correspond to certain special areas in the mold, such as near the inlet or outlet, where there may be local temperature fluctuations or measurement errors. But overall, the temperature field inside the mold is relatively stable.

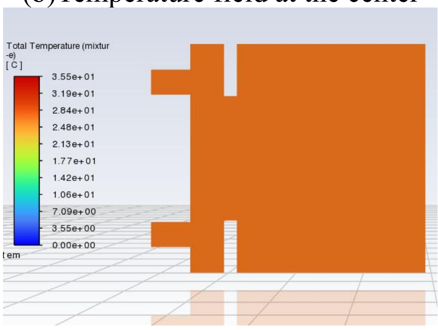
4.3 Condition: Viscosity of 500



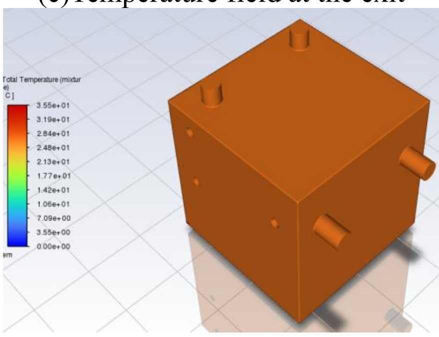
(a)Temperature field at the entrance



(b)Temperature field at the center



(c)Temperature field at the exit



(d)Isometric view of temperature field

Figure12. Temperature Field Inside the mold with a Viscosity of 500 Pa.s

From Figure 12, it can be clearly seen that under the condition of viscosity of 500 Pa · s, even if the grouting speed is maintained at 1m/s, the fluid phase still chooses air phase and high polymer fluid phase for simulation. The temperature fields at the entrance, central position, and exit remain stable at around 28.6 ℃. This result indicates that regardless of changes in fluid viscosity, the temperature field of polyurethane during flow and diffusion in the mold can be maintained within a relatively constant range without significant fluctuations. This temperature stability means that polyurethane can maintain a relatively consistent physical state during the molding process, which helps to improve the quality and consistency of the molded parts. In addition, the simulation results also show that even though the temperature slightly increases at the center of the mold, reaching around 35.5 ℃, the overall temperature field remains constant. This further confirms the thermal stability of polyurethane during the flow process, even in the case of increased viscosity leading to increased flow resistance, the temperature change is still not significant.

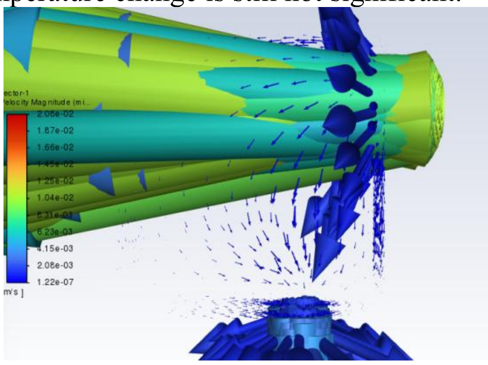


Figure 13. Temperature Field Vector Diagram

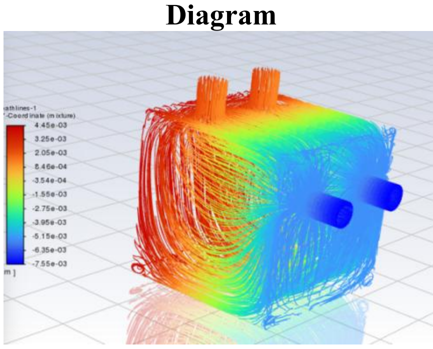


Figure 14. Temperature Field Trace Diagram

By observing Figure 13, it can be seen that the fluid flows faster in the inlet and outlet areas of the mold, while the velocity is slower in the cavity area inside the mold. This may be due to the complexity of the internal structure of the mold, such as the presence of narrow channels or obstacles. The temperature of fluids varies in different regions, which may be due to heat exchange between the fluid and the surrounding environment or solid walls at different temperatures during the flow process. The temperature in the inlet and outlet areas is higher, possibly because these areas are closer to the heat source or heat input point, while the temperature in other areas is relatively lower.

According to Figure 14, the temperature field trace inside the mold is shown, with color bars indicating the range of temperature changes, from blue (lower temperature) to red (higher temperature). The temperature of the fluid at the inlet is relatively high, and as it flows inside the mold, the temperature gradually decreases. At the junction of the front and bottom of the mold, the temperature change of the fluid is more obvious, which may be due to slow flow velocity or local heat dissipation in these areas.

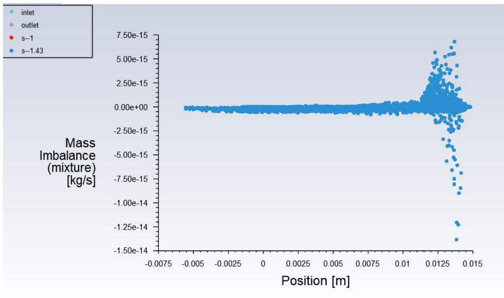


Figure 15. Temperature Field Scatter Diagram

Figure 15 is a temperature field scatter plot, from which it can be seen that the temperature values of most data points are concentrated around 12.6 ℃, indicating a relatively uniform temperature distribution inside the mold. This indicates that during the simulation process, the temperature change of the polyurethane fluid is not significant, and the thermal environment inside the mold is relatively stable. The uniformity of this temperature helps ensure stable flow and curing of polyurethane in the mold, reducing uneven flow and internal stress caused by temperature differences. The temperature values of a few data points in the figure differ significantly from 12.6 ℃, which may correspond to certain special areas in the mold, such as near the inlet or outlet, where there may be local temperature fluctuations or measurement errors. But overall, the temperature field inside the mold is relatively stable.

5. Conclusion

(1) In this study, the flow characteristics of polymer-polyurethane fluid in a self-designed polymer fluid flow control device were studied by ANSYS Fluent numerical simulation system. The device adopts a cubic cavity structure of 300 mm × 300 mm × 300 mm, and the top cover plate is equipped with a replaceable injection hole module, which can realize two injection methods of central hole and eccentric hole.

(2) In the numerical simulation section, a simulation analysis model for the diffusion of polymer fluid in a mold was established, and the applicability of the numerical model was tested using a slurry casting model test device. The study found that the temperature field of polyurethane remained relatively stable during the flow process, and even with changes in viscosity, the temperature fluctuation range was still minimal. The distribution of the pressure field was mainly influenced by the geometric structure of the mold, rather than the viscosity of the fluid itself. In addition, the analysis of the outlet flow rate showed that the outlet velocity of the fluid decreased with increasing viscosity, providing an important basis for optimizing production efficiency and product quality.

Acknowledgments

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